First Alignment of the CMS Tracker and Implications for the First Collision Data

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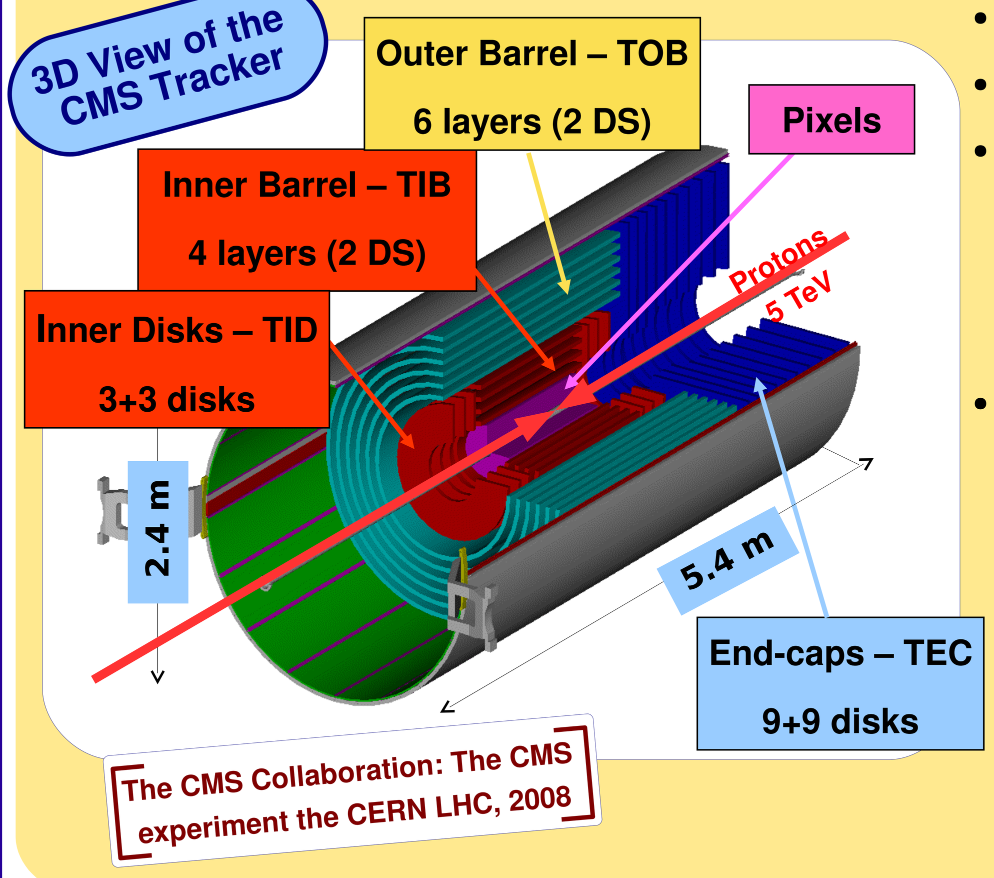
The CMS Tracker Layout

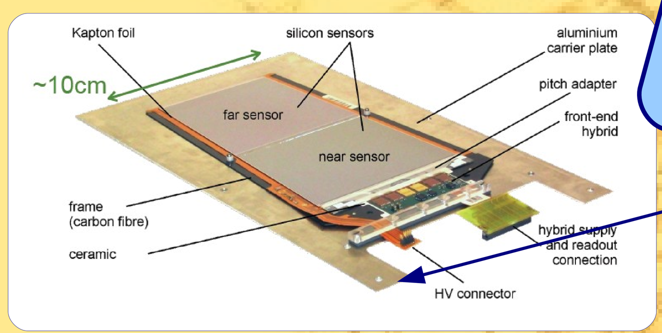
- The CMS Tracker is the main tracking device of the CMS experiment, entirely realized with silicon technology and it is the largest detector of its kind in the world

3D View of the CMS Tracker



The CMS Collaboration: The CMS experiment at the CERN LHC, 2008

- Volume 24 m^3 / covered area 200 m^2
- Running temperature: -10° C
- STRIP detector:
  - *15148 modules:* (pitch 80 – 205 μm)
  - single point resolution of 20 – 60 μm
  - 2D measurements from DS modules, tilt 100mrad
- PIXEL detector:
  - *1440 modules:* (pitch 100(r) *x* 150(z) μm^2)
  - resolutions: 9(r) *x* 20(z) μm

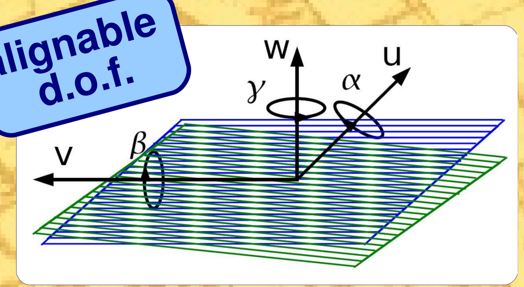


A CMS Tracker Silicon Strip Module

Alignment goal

- Tracker alignment in one of the crucial factors to reach the design resolution of the CMS detector.
- Goal: nail down to a few μm the positions of all 16,588 (x 6 dof) silicon modules of CMS Tracker.

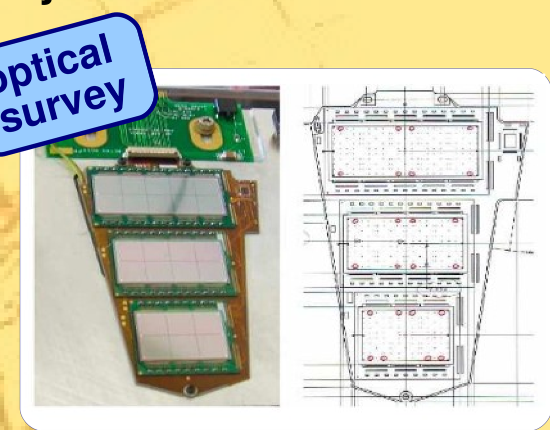
alignable d.o.f.



- The six alignable degrees of freedom of a CMS Tracker module $\Delta p = (\Delta u, \Delta v, \Delta w, \alpha, \beta, \gamma)$
- 3 translations and 3 rotations w.r.t the nominal geometry have to be determined

- Alignment strategy in CMS: Use all available data sources.
  - Surveys (optical/mechanical/...)
  - Laser Alignment
  - *Track Based Alignment*

optical survey



- From older experiments: ultimate precision is achieved using track based alignment, i.e. particles crossing *in situ* the Tracker volume

Track Based Alignment

- Define a Global Track χ^2 function:

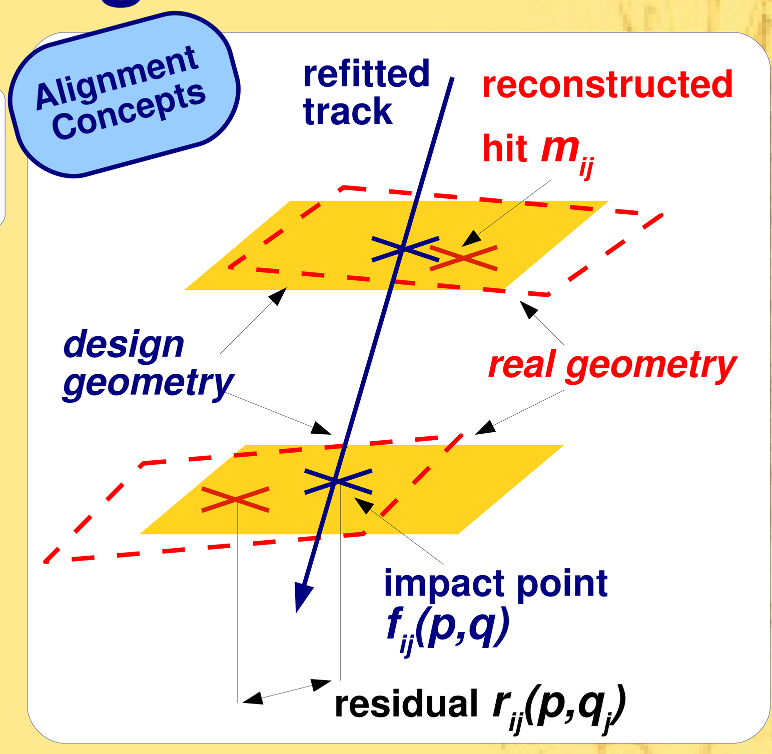
$$\chi^2 = \sum_{j=1}^{N_{tracks}} \sum_{i=1}^{n_{hits}} r_{ij}^T(p, q_j)\, V_{ij}^{-1}\, r_{ij}(p, q_j)$$

$$r_{ij}(p, q_j) = m_{ij} - f_{ij}(p, q_j)$$

where:

- V_{ij} = covariance matrix from fit
- *p = alignment parameters (module position/orientation)*
- q_j = track parameters
- $r_{ij}(p,q_j)$ = residual: difference between measured position m_{ij} and position extrapolated from fit $f_{ij}(p,q_j)$ (depending on p and q_j)
- *Aligment algorithms attempt to minimize this χ^2 function and therefore track residuals*

Alignment Concepts



- The challenge is to determine at O(10μm) corrections for the 6 d.o.f (3 rotations + 3 translations) for each of the > 16k modules in CMS Silicon Tracker!
- A complex system of equations to be solved: 16.5k modules *x* 6 d.o.f. ≃ 100k unknowns
- Fast and robust algorithms are deployed in the CMS framework.

Alignment Algorithms

Local Iterative Method: "Hit and Impact Points"

[arXiv:0809.3823]

$$\chi^2_{loc} = \sum_i^{hits} r_i^T(p_m)\, V_i^{-1}\, r_i(p_m) + \sum_*^{surveys} r_*^T(p_m)\, V_*^{-1}\, r_*(p_m)$$

Tracks + Surveys to fix all the alignable degrees of freedom

$$\Delta p_m = \left[\sum_i J_i^T V^{-1}{}_i J_i\right]^{-1} \left[\sum_i J_i^T V^{-1}{}_i r_i\right]; \quad J_i = \partial r_i / \partial p_m$$

Pros	full *Kalman Filter* track model	simple implementation, all d.o.f.
Cons	ignore correlations in one iteration	large CPU with many iterations

Global Method: "Millepede II"

[NIM A 566, 5 2006]

Linearize track model $f_{ij}(p,q_j)$ as a function of the aligment parameters *a*

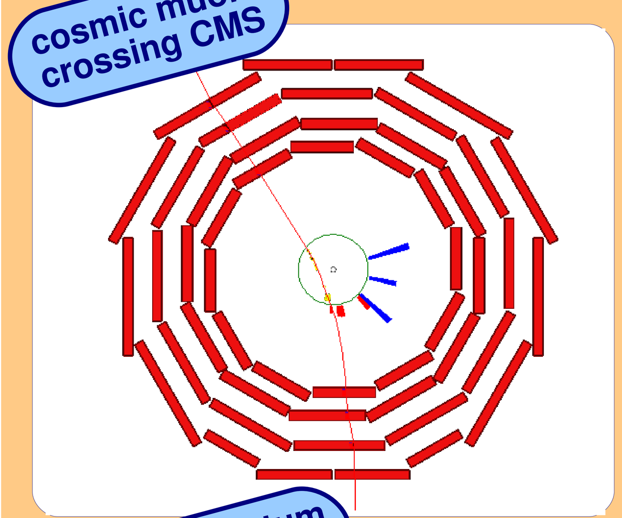
$$\chi^2(p,q) = \sum_j^{tracks} \sum_i^{hits} \frac{\left(y_{ij} - f_{ij}(p_0, q_{j0}) + \frac{\partial f_{ij}}{\partial p} a + \frac{\partial f_{ij}}{\partial q_j} \delta q_j\right)^2}{\sigma_{ij}^2}$$

Minimization leads to the matrix equation $Ca = b$ which has to be solved to extract *a*

Pros	model module correlations	less CPU with one or few iterations
Cons	simple helix trajectory model	large matrix may limit total N of alignables

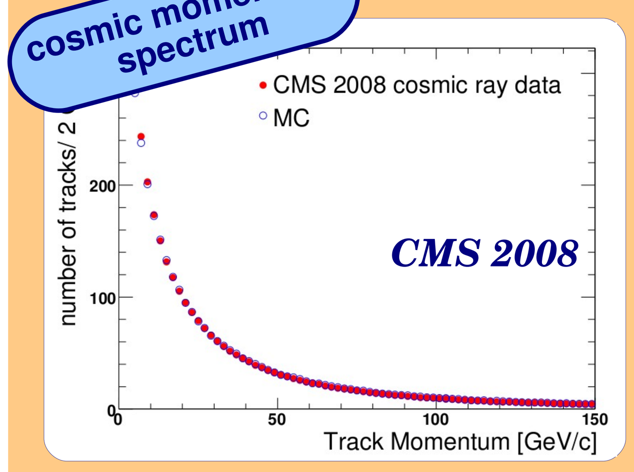
Alignment with cosmic rays

cosmic muon crossing CMS



- First complete alignment of the CMS Traker performed at the Cosmic Run at Four Tesla (CRAFT)
- A "*global run*": all CMS subdetectors participating to the data taking
- Data taking 24/7 for 3 weeks (Oct 2008)
- Major milestone demonstrating CMS capability of running over long periods
- 300 Million cosmic muon triggers collected @ 3.8 T
- Chance of performing alignment and calibration as an input to collision data taking

cosmic momentum spectrum



Alignment Strategy

- Run a multi-step approach for both algorithms:
  - large *structure* movements (coherent *v* alignment of Single Sided modules)
  - Alignment of the two sides of 2D strip *modules (units): u,w,γ*
  - module-level alignment of strip and pixel modules

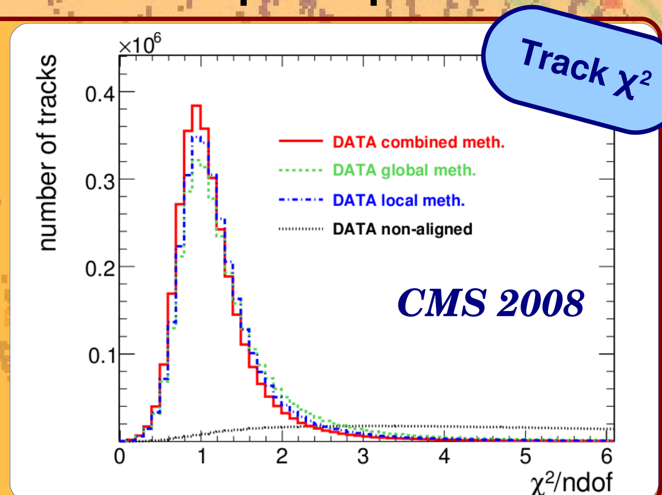
Final Approach

Get the best from both algorithm, combining the two:

1) run the global method → solves global correlations efficiently
2) run the local method → solves locally to match track model in all degrees of freedom

⇒ All the three results are compatible but the Combined shows the best performance

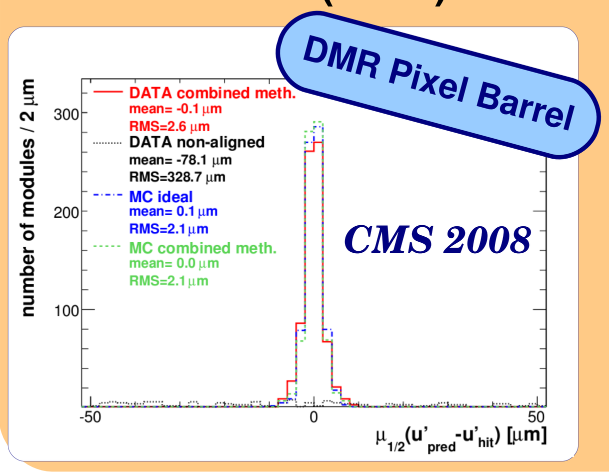
Track χ^2



Validation Methods

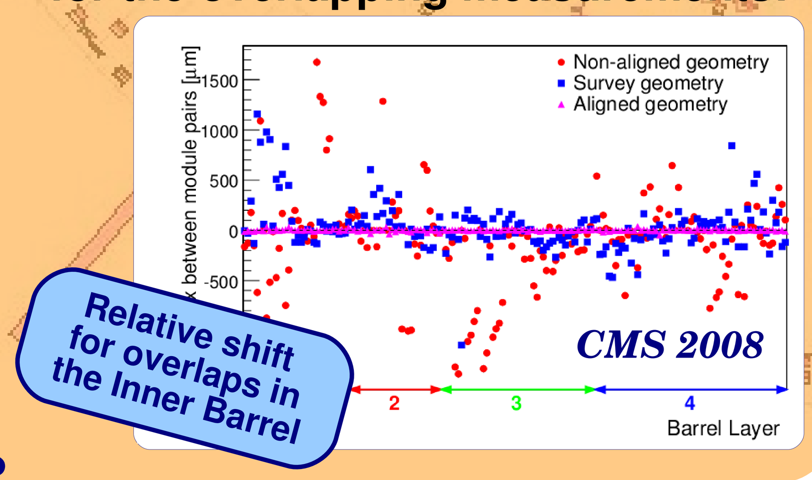
- Alignment recovers the average position of modules along the sensitive coordinate:
  - check the Distribution of Median of Residuals (DMR)

DMR Pixel Barrel



Sensitive to the *incoherent displacements* of the modules w.r.t. each other along the *sensitive coordinate*

- Idea: use tracks passing in regions where modules overlap within a layer
- Check difference of residual values for the overlapping measurements:



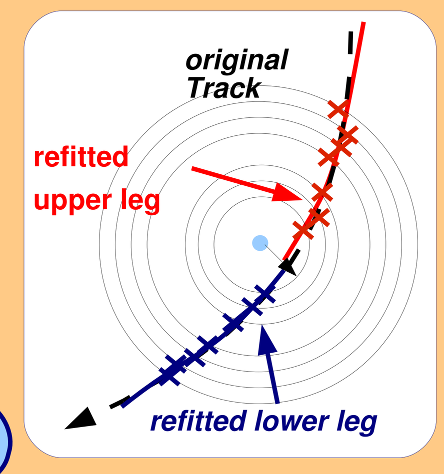
Relative shift for overlaps in the Inner Barrel

Implications for first collisions

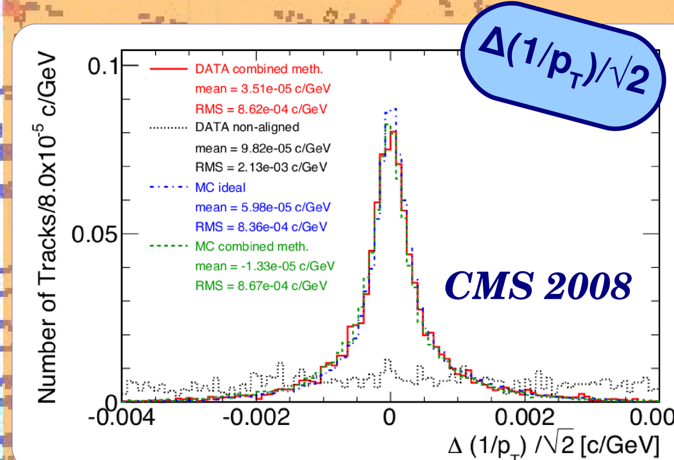
- The all-silicon design of the tracking system of the CMS experiment is expected to provide 1-2% resolution for 100 GeV tracks and an efficient tagging of b-jets.

Impact of Alignment on tracking

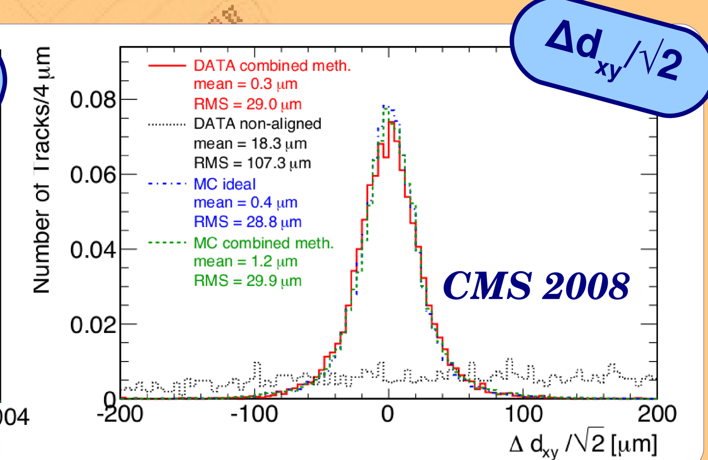
- Idea: split the cosmic tracks along impact parameter and compare the five track parameters $X = (p_T, d_{xy}, d_z, \varphi_{tk}, \theta_{tk})$ of top and bottom halves
- Define residuals as: $r = \frac{X_{top} - X_{bottom}}{\sqrt{2}}$



$\Delta(1/p_T)/\sqrt{2}$



$\Delta d_{xy}/\sqrt{2}$

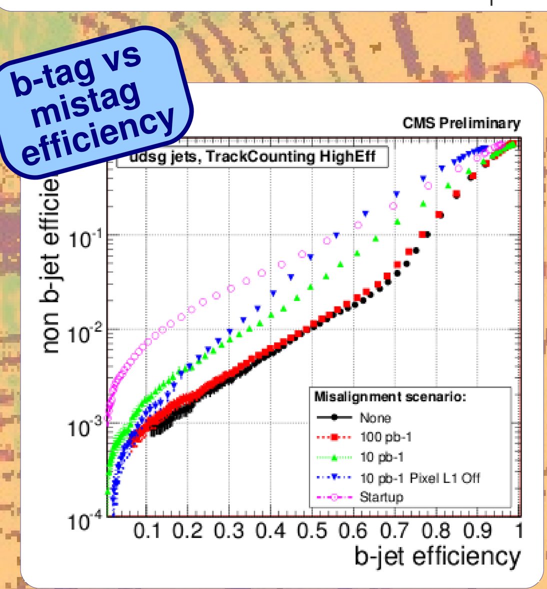


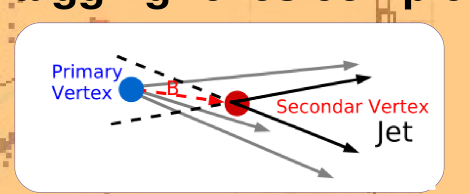
- Alignment has a dramatic impact on the resolution of:
  - d_{xy} (transverse impact parameter)
  - $1/p_T$ (track curvature)

Monte Carlo Studies

- B-tagging relies completely on tracking performance:

b-tag vs mistag efficiency

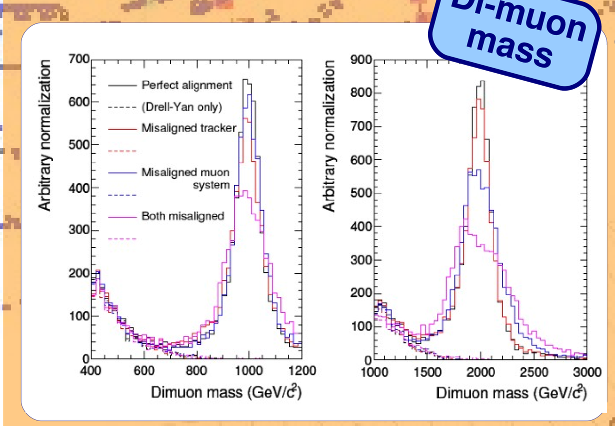




Needs clear separation between primary and secondary vertices

- all b-tag algorithm are sensitive to alignment
  - both positions and errors important
- Several misalignment scenarios considered
- Flight distance significance and hence b-tag efficiency improves with accumulation of statistics for alignment

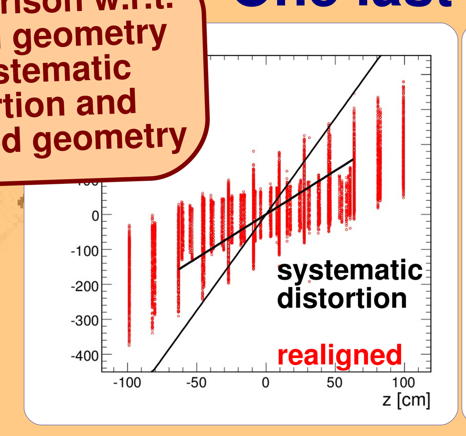
Di-muon mass

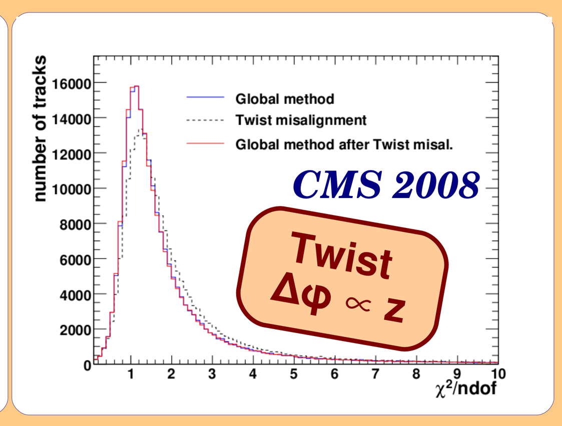


- Alignment impact on di-muon invariant mass resolution.
- Alignment is critical for high p_T muons

One last caveat ...

Comparison w.r.t. design geometry of systematic distortion and realigned geometry





- There are systematic distortions which affect slightly the χ^2 but bias significantly physics results
- As an example: twist distortion cannot be recovered only with cosmic rays ⇒ collisions needed!